ADMINISTRATIVE INFORMATION

1. **Project Name**: Development and validation of a coupled combustion space/glass bath furnace simulation

2. **Lead Organizations**:

Argonne National Laboratory
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3. **Principal Investigators**:

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4. **Project Partners:**

Owens Corning	Christopher Jian Shivakumar Kadur
Visteon Glass Systems	Ed Boulos, Jian Wang
Libbey, Inc.	Ed Olson
Osram Sylvania Products, Inc.	William Anderson
Purdue University	Prof.Raymond Viskanta
Purdue University Calumet	Prof. Chenn Zhou
Mississippi State University	Prof. Robert Cook
Shell Glass Consulting	Jim Shell

5. **Date Project Initiated**: November 1, 1998

6. **Completion Date**: December 31, 2003

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:** This project is the second phase of a program to develop a "state of the art" glass furnace model which couples the combustion space to the glass melt through a rigorous spectral radiation model. The key technical objectives of this follow on program were to incorporate glass chemistry models into the glass melt, activate gaseous phase transport (bubbles/foam) in the glass melt, develop/incorporate chemistry/nucleation models to model the transport of gases/particulates emanating from the batch/molten glass into the combustion space, develop/incorporate glass quality indices, develop/validate several furnace simulations of different types of furnaces, disseminate a beta version of the code to the glass industry participants (GMIC members), and to transfer the technology (code) to the entire glass industry.

8. **Technical Barrier(s) Being Addressed:** A substantial effort has been expended by several organizations during the past decade to develop furnace models to predict furnace performance. These efforts have had varying and limited objectives. The models developed generally had been based on major underlying assumptions that substantially impacted the predictions. What was missing was a 'unified' glass furnace model that incorporated as much of the physics into the codes as

was achievable while still having the code being 'user-friendly.' The first step in this project was to develop/incorporate these advanced models. In order to gain confidence in these models, in-furnace measurements were required to validate the trends computed by the models. Very little experimental data had been obtained from operating furnaces which has hampered assessment of the validity of previous models. This program sought to address modeling deficiencies, the lack of in furnace measurements, and sought to create a simulation that a non-CFD expert could use effectively.

9. **Project Pathway:** This program was structured to develop a validated CFD furnace model that will have the advanced computational capabilities which can be used by the glass industry to investigate opportunities that may improve glass quality and productivity (glass throughput) while minimizing energy use and gaseous and particulate emissions. After extensive discussions with the industrial partners, the following advanced computational capabilities were identified: (1) advanced radiation models to properly account for all major contributions to the surface heat flux, (2) explicit (not post-processed) multiphase (liquid, solid, bubble flow) capabilities in the melter, (3) chemical reactions in the melt, and (4) the effects of and the formation of foam on the glass surface. The successful development and incorporation of these models will provide the industry with a state of the art furnace model that will represent a step change in analytical capability. Along with these computational advances, a user-friendly pre- and post-processors have been developed which allow a non-CFD expert to build, execute and evaluate furnace models. The ultimate utility of this state of the art model will be demonstrated in the application of the model by the furnace engineers/operators of the industrial partners in order to achieve and/or maintain predetermined glass quality and furnace performance targets.

10. **Critical Technical Metrics:** All key technical milestones of the Part I program (which was completed in FY 2001) have been achieved. These milestones were:

    (1) Construct and validate a computational fluid dynamics (CFD) based combustion space model that incorporates a rigorous treatment of spectral radiation from combustion species such as H_2O, CO_2 and soot and radiation from the crown.
    (2) Develop a simulation of the glass melt with ANL's CFD code which has inherent multi-phase flow capabilities and directly incorporate models of the glass batch and foam region.
    (3) Couple the combustion space/glass melt models into a simulation of a selected furnace.
    (4) Make measurements (in the furnace modeled) of key furnace operating parameters to provide a data base for validation of the model.
    (5) Conduct validation studies of the furnace model.

A workshop was held for the GMIC membership in October 2002. At this workshop, a demonstration version of the GFM code (version 1.0) was given to the attendees to acquaint them with the features and capabilities of the code.

Key technical objectives (milestones) for the Part II follow-on program were:

    (1) Incorporate glass chemistry models into the glass melt/batch to compute and track key solid, gas, and liquid species throughout the melt.
    (2) Activate the gaseous phase transport equations built into the glass melt model with source terms derived from the chemistry models to compute gaseous species production, bubble nucleation and growth, dissolution, and release from the glass melt surface (foaming).
    (3) Develop and incorporate chemistry and nucleation models of particulate formation for the gases emanating from the glass melt and batch into the combustion space.
    (4) Develop and incorporate glass quality indices into the simulation to facilitate optimization studies with regard to productivity, energy use, and emissions.

(5) Develop and validate furnace simulations of three additional furnace types used in the industry.
(6) Make available a beta version of the furnace model to the program participants and assist them in the use of the code for the conduct of parametric and sensitivity studies of their furnaces in order to provide feedback on code utility.
(7) Conduct a workshop for the entire industry at the conclusion of the program where the code, furnace simulation and all data and information derived from the program will be made available to all. Assistance in the use of the code and simulations will be made available through a support center that will be created at the conclusion of the program.

To date, milestones 1, 2, 4, 5, and 6 have been completed. As discussed in the following, Section 13, milestone 3 was eliminated. The need for the conduct of a formal workshop for the industry (Milestone 7) is being reassessed in view of the fact that a follow-on program has been initiated to transfer the GFM code to the industry. All companies who request a no-cost trial license to use GFM will be trained to use the code and provided free technical support for a limited time period. Also, a final report containing all data and information derived from the program will be issued and be distributed to the industry. The decision as to whether a formal workshop will be held will be made in consultation with DOE/EE and GMIC.

PROJECT PLANS AND PROGRESS

11. Past Accomplishments

The following is a list of the final accomplishments during the past reporting period:

(1) Simulations of several furnaces selected by the industrial partners were developed with the GFM 2.0 code.
(2) Parametric, sensitivity and optimization studies, using the simulations developed, were completed.
(3) A foam model was incorporated into the melt model. A model that accounts for the effect on the radiative heat flux by the calculated foam layer was incorporated.
(4) Advanced quality indices have been incorporated into the melt code.
(5) A users manual and a final report is in the process of being written

12. Future Plans:

There are no current plans for continued development of the Glass Furnace Model codes. However, as noted, technical transfer of the code to industry is underway through a follow-on program.

13. Project Changes

As discussed at the 2003 Program Review meeting, the decision was made to eliminate the task to model the chemistry, nucleation, and transport of particulates in the combustion space in order to focus the limited remaining resources on providing technical support to the industrial participants for the Beta Test of the GFM code and the conduct of the parametric, sensitivity, and optimization studies. Also, because of the unavailability of data on the principal controlling reactions for the selected glasses and associated kinetic models, the scope of the effort relative to developing and testing the multiphase models in GFM 3.0 had to necessarily be reduced. In order to complete development and testing of the multiphase models in the code, simplified reduced chemistry models with one step batch and two step fining reactions were incorporated into the code. Users of the code who wish to incorporate their proprietary chemistry models into the GFM 3.0 code will be able to do so since the code has been structured to allow inclusion and use of such models. The typical code user, however, will require considerable assistance (technical support) from ANL to incorporate their proprietary models into the code since this must be done through changes in the source code. These changes in work scope were made in consultation with and concurred by the industrial partners.

14. **Commercialization Potential, Plans, and Activities**

A commercialization plan to transfer the GFM to the industry is being implemented. A brochure describing the capabilities of the GFM has been developed and distributed to the glass industry. A no-cost trial license for the use of the GFM code is being provided to interested users and these users will be provided no-fee technical support for up to six months. After this free trial period, a one-time nominal licensing fee, in accordance with a fee schedule developed in consultation with the industrial participants and DOE, will be levied. A Code User Group will be formed whose membership comprises the code licensees. The licensee is expected to become proficient in the use of the code during the no-fee technical support period. It is planned that the user group will meet periodically to discuss code use issues and to share experiences. They will define/prioritize code improvements that ANL will strive to develop during this period that are consistent with the available resources. The user group will also be charged with defining and implementing a long term technical support strategy beyond the initial six month no-fee trial period.

15. **Patents, publications, presentations**

Copyrights:

The Glass Furnace Model software (GFM 1.0) copyrighted 05/14/01
The Glass Furnace Model software (GFM 2.0) copyrighted ANL-SF-01-030b 05/1702

Publications:

1. “Computer Modeling of Glass Furnace Flow and Heat Transfer,” S.L. Chang, B. Golchert, C.Q. Zhou, 7th International Conference on Advances in Fusion and Processing of Glass, July 27-30, 2003, Rochester, NY (invited).

2. “The Effects of Gases Emitted from Batch/Glass Reactions on the Combustion Space Flow Field,” B. Golchert, S.L. Chang, C.Q. Zhou, ASME National Heat Transfer Conference, July 2003, Las Vegas, NV.

3. “Modeling and Preliminary Validation of a Regenerative Glass Furnace using the ANL Glass Furnace Model,” B. Golchert, S.L. Chang, E. Olson, National Heat Transfer Conference, July 2003, Las Vegas, NV.

4. “Modeling of Radiation Heat Transfer in Glass Melts,” B. Golchert, S.L. Chang, C. Zhou, , IMECE 2002, Nov. 17-22, 2002, New Orleans, LA.

5. “A Simulation Approach for Bubble Flow in a Glass Melter,” S.L. Chang, B. Golchert (ANL), C.Q. Zhou (Purdue Calumet), IMECE 2002, Nov. 17-22, 2002, New Orleans, LA.

6. “Implementing Chemical Reactions in the Glass Melt of the ANL Glass Furnace Model,” S.L. Chang, C.Q. Zhou, and B. Golchert, the Glass and Optical Materials Division of the American Ceramic Society, Fall 2002 Meeting, Pittsburgh, PA.

7. "A Numerical Investigation of Electric Heating Impacts on Solid/Liquid Glass Flow Patterns," S.L. Chang, C.Q. Zhou, and B. Golchert, AIAA National Heat Transfer Conference, 24-26 June 2002, St. Louis, MO.

8. "Application of the ANL Glass Furnace Model to Industrial Furnaces," C.Q. Jian (Owens Corning), J. Chumley (Techneglas), E. Oslon (Libbey, Inc.), E. Boulos (Visteon Corp.), W. Anderson (Osram-Sylvania), S.L. Chang, B. Golchert, M. Petrick (ANL), C.Q Zhou (Purdue Calumet), American Ceramic Society Annual Meeting, 24-27 March 2002, St. Louis, MO.

9. "Simulation of Multi-Phase Glass-Melt Flows in a Glass Melter," S.L. Chang, C.Q. Zhou, B. Golchert, and M. Petrick, IMECE 2001, Nov. 11-16, 2001, New York, NY.

10. "An Investigation of the Effects of Firing Patterns on Heat Transfer and NO_x Formation in a Glass Furnace," S.L. Chang, B. Golchert, C.Q. Zhou, and M. Petrick, National Heat Transfer Conference, Anaheim, CA, June 2001